Improving Our Understanding of 1D Site Response Model Behavior: Physical Insights for Statistical Deviations from 114 KiK-net Sites

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1. Introduction

- Site response models are associated with large uncertainties and sometimes poorly replicate observed ground motions. This study seeks to better understand site response model uncertainty by pairing statistical analyses with physical insights into site behavior.
- Predictions for 5626 records at 114 vertical seismometer arrays of Japan's Kiban-Kyoshin network (KiK-net) are computed using the linear (L) and equivalent-linear (EQL) site response models in SHAKE, and nonlinear (NL) site response model in DEEPSOIL. All models use the one-dimensional (1D) total-stress approach (Fig. 1).
- Statistical analyses are performed to quantify the models' uncertainties, and a number of physical hypotheses for explaining poor site response model performance are tested.
- This study builds upon Kaklamanos et al. (2013), which analyzed L and EQL site response models at 100 KiK-net sites, Kaklamanos et al. (2015), which analyzed L, EQL, and NL site response at a subset of 6 validation sites; and Kaklamanos and Bradley (2015), which analyzed the L, EQL, and NL model residuals at 114 sites.

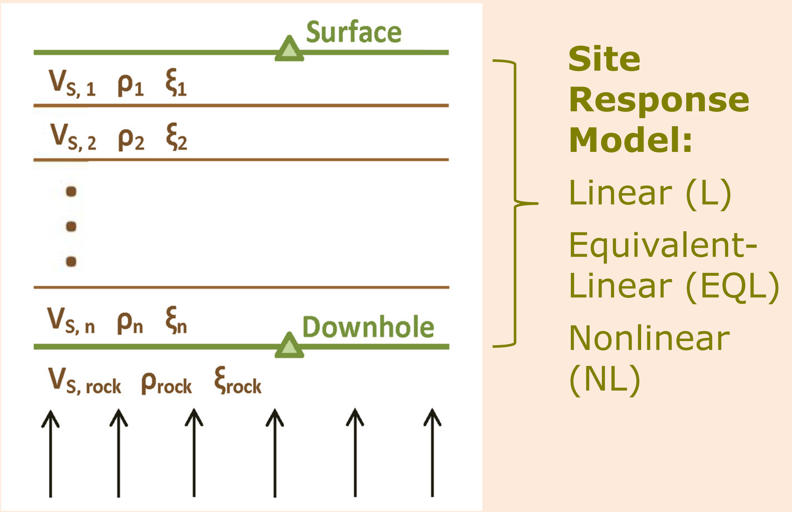


Figure 1. Schematic of a site response model and validation framework for surface-downhole arrays.

2. Statistical results

- In the aggregate, all 1D site response models (L, EQL, and NL) are biased towards underprediction of ground motions at short spectral periods (high frequencies), where nonlinear effects are strongest; however, the EQL and NL model biases are smaller than the L model bias (Fig. 2, Table 1).
- We find that Arias Intensity I_a (which encompasses a range of high frequencies important for nonlinear site response) is a particularly useful intensity measure for assessing site response model uncertainty.
- When the bias for Arias Intensity is separated by bins of maximum shear strain (Fig. 3), it is shown that all models offer their most severe underpredictions for small-strain motions. The importance of being able to accurately predict site response for small amplitude inputs motion is the ability to be able to use small events to predict what might happen at a specific site for larger events.
- Cumulative measures of I_a allow us to compare how the models deviate throughout the duration of the earthquake record. The comparison of I_a as a function of time shows that the EQL model severely underpredicts large-strain ground motions (for approximately γ > 0.05%) near the beginning of strong shaking (because the shear modulus is underestimated and damping is overestimated), but that the EQL and NL model biases converge when the entire record is considered. As expected, the L model overpredicts large-strain ground motions when the entire record is considered.

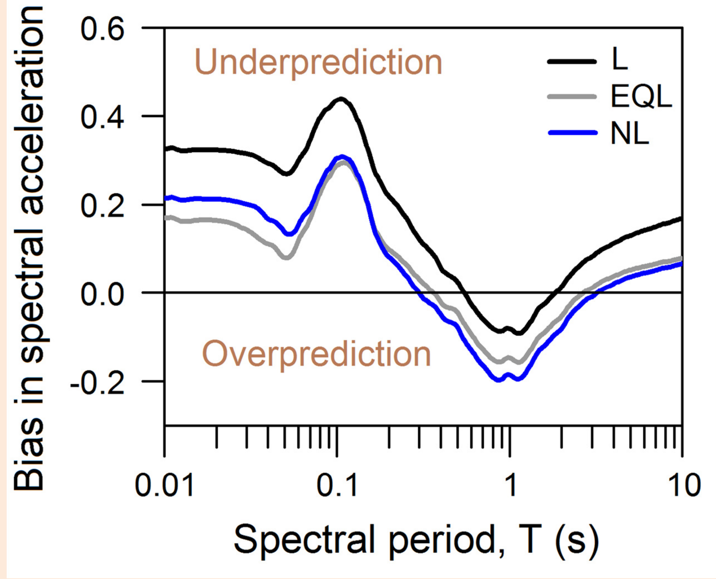


Figure 2: Model biases versus spectral period, across all 5626 ground motions and 114 sites in this study

Table 1. Model biases for whole dataset: PGA and I_a

	L	EQL	NL
Peak ground acc.	0.325	0.169	0.213
Arias Intensity	0.573	0.190	0.138

$$\text{Bias} = \text{mean}\left[\ln(\text{IM}_{\text{obs}}) - \ln(\text{IM}_{\text{pred}})\right],$$

where IM_{obs} and IM_{pred} are the observed and predicted intensity measures

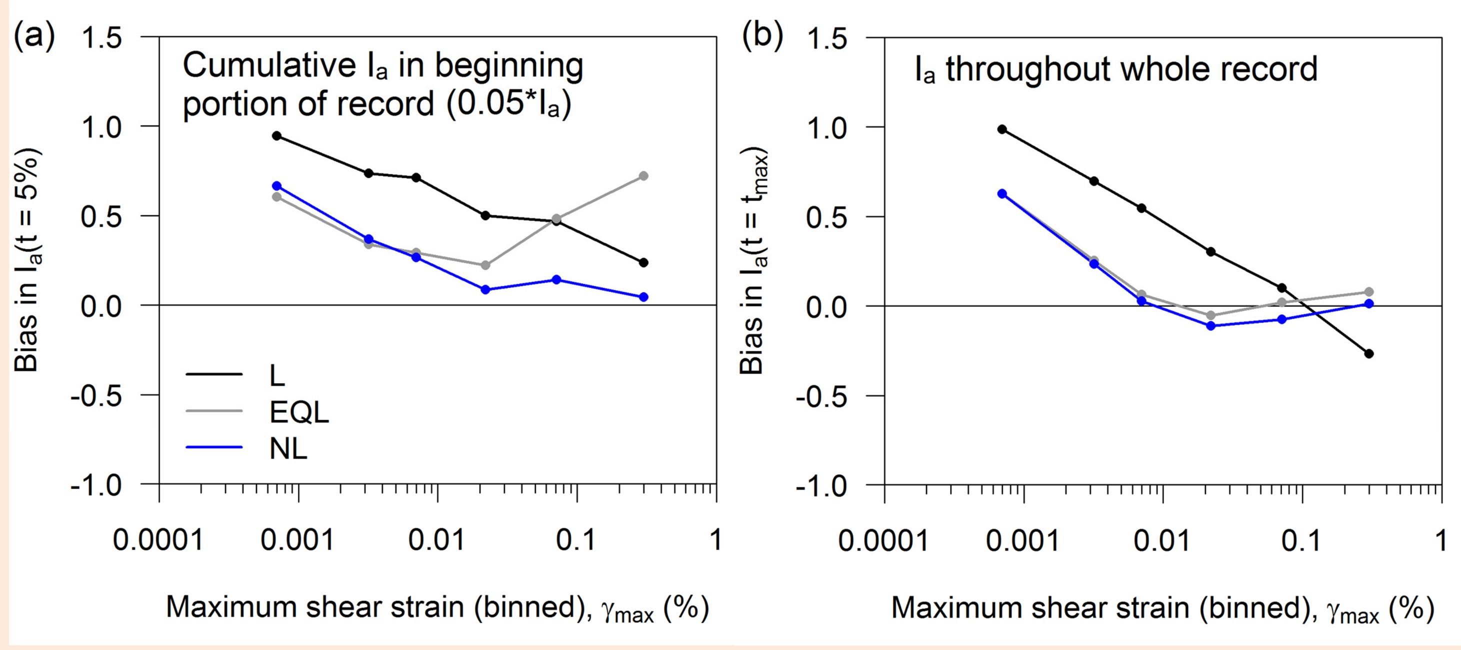


Figure 3: Model biases for Arias Intensity binned by maximum shear strain for (a) **5% cumulative I_a**, representing the early part of the record near the beginning of strong shaking; and (b) **total I_a**, representing the energy throughout the duration of the record.

3. Physical adjustments to profiles and material parameters

- In order to better understand the underprediction of high-frequency ground motions by all site response models, we tested four physical hypotheses at a subset of sites: IWTH08 (NEHRP Site Class D, V_{S30} = 305 m/s) and IWTH02 (NEHRP Site Class C, V_{S30} = 390 m/s).
- These results provide insights into how 1D site response model predictions may be improved by alternative assumptions regarding the soil profile and material parameters (Fig.4). The number of sites considered for these physical tests (currently two) is currently being expanded to corroborate these initial findings.

	Hypothesis 1: Apply a depth-dependent V_S gradient within layers	**Hypothesis 2: Randomize the V_S profile**	**Hypothesis 3: Decrease the small-strain damping ratio**	**Hypothesis 4: Increase the small-strain shear modulus**
HYPOTHESIS	We hypothesize that the V_S profiles provided on the KiK-net website may be too coarse, and that the impedance contrasts may be too sharp. Due to increasing confining pressures, constant or increasing densities with depth will lead to an increase in V_S with depth in a given layer.	We hypothesize that 1D site response models may not accurately represent three-dimensional (3D) subsurface heterogeneity, and that adding uncertainty to the V_S profiles may help better capture variability in soil properties.	Since hysteretic damping theoretically approaches zero at small strains, we hypothesize that the assumed small-strain damping in the constitutive models may be too large.	We hypothesize that field measurements may underestimate the small-strain shear modulus (G_{max}) because larger strains (~0.001%) may actually be incurred in the soil during testing (Fig. 8).
ACTION	Within each layer, the constant value of V_S is replaced with a depth-dependent exponential gradient centered on the median V_S for the layer (Fig. 5).	Five randomized profiles are generated using the Toro (1995) model for V_S uncertainty, and the median results of the randomized profiles are analyzed (Fig. 6).	In all models, the small-strain damping ratio has been reduced by half (Fig. 7).	Because the shear modulus G measured in the field might be slightly less than the true G_{max}, we have increased G_{max} by 10% in all analyses.
RESULT	The assumption of constant V_S over a large depth leads to unrealistically large strain localizations and dissipation of high-frequency energy, and the depth-dependent gradient resolves this issue. Noticeable reductions in model bias are observed when using the depth-dependent V_S gradient (Fig. 4).	In general, the randomized profiles do not present a significant improvement from the original profile (Fig. 4). However, this approach does reduce the bias near the site period (particularly for IWTH08), implying that the use of 1D site response models lead to excessive resonances at the site period. Overall this approach might work better for other sites that are known to be more heterogeneous.	The revised small-strain damping leads to significant improvements in the site response predictions at both small and large strains (Fig. 4). The improvement of small-strain prediction is particularly important for regions that lack strong ground motion records.	Adjusting G_{max} in this manner leads to small changes in the V_S profile ($V_s = \sqrt{G_{max}/\rho}$) and therefore produces insignificant differences in the site response predictions (Fig. 4).

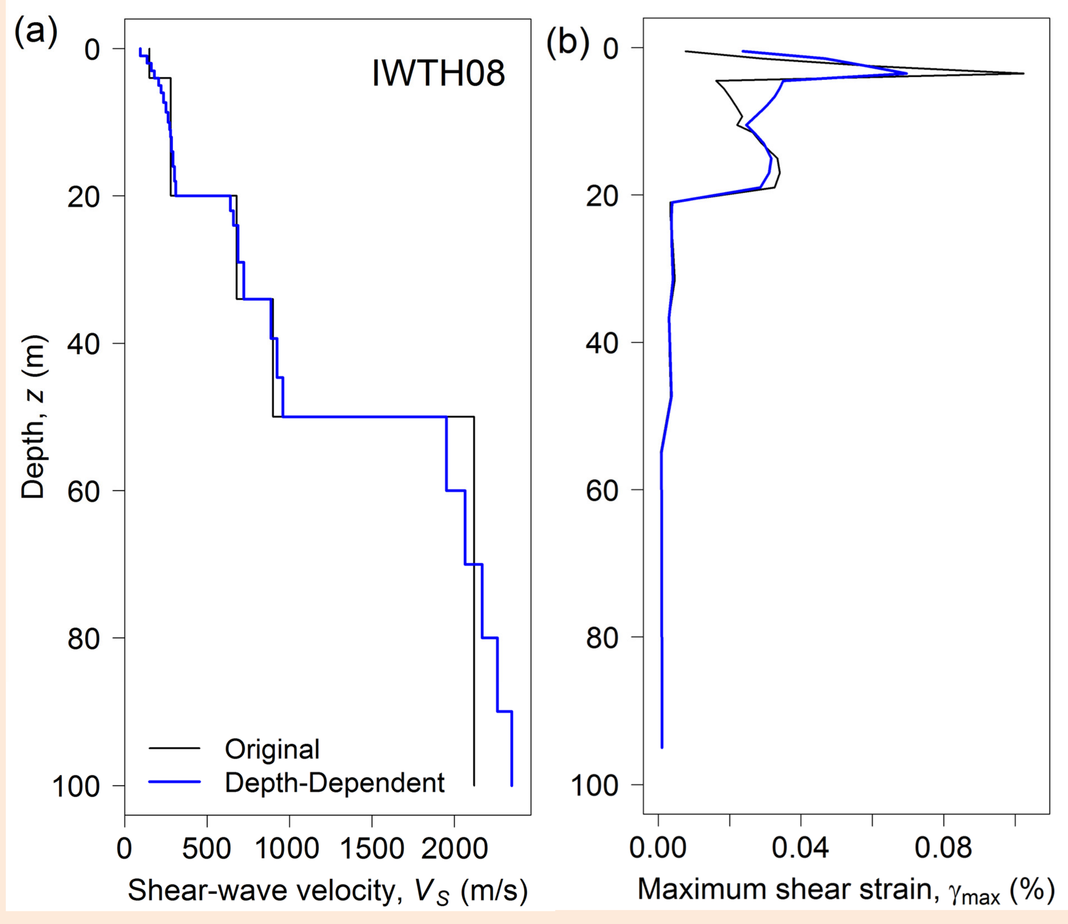


Figure 5: (a) Original and depth-dependent V_S profiles for IWTH08, (b) comparison of maximum shear strain profiles for a strong event (the M_w 6.8 Iwate earthquake of 24 July 2008; PGA = 0.392g).

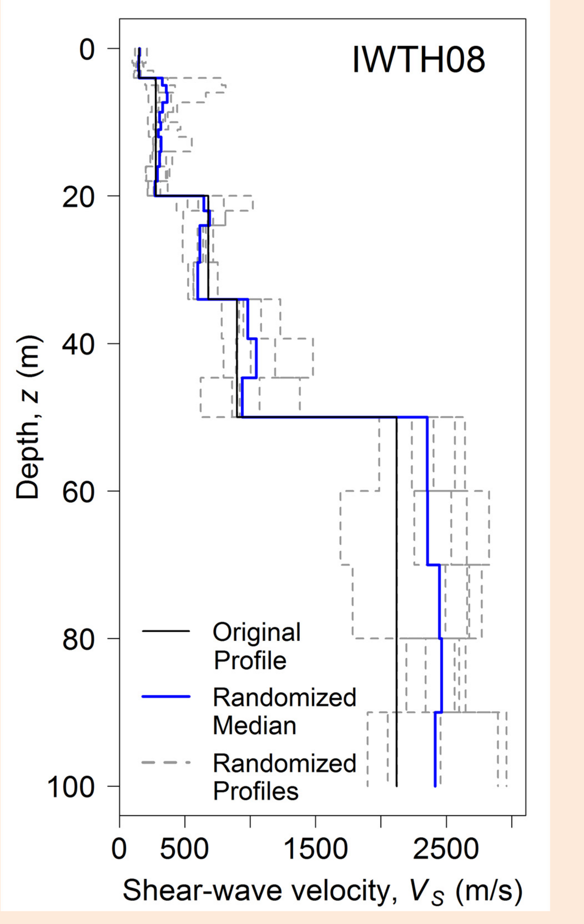


Figure 6: Five randomized V_S profiles for IWTH08, along with the median and original profiles.

Figure 7: Original and revised damping curves for the surficial layer at IWTH02.

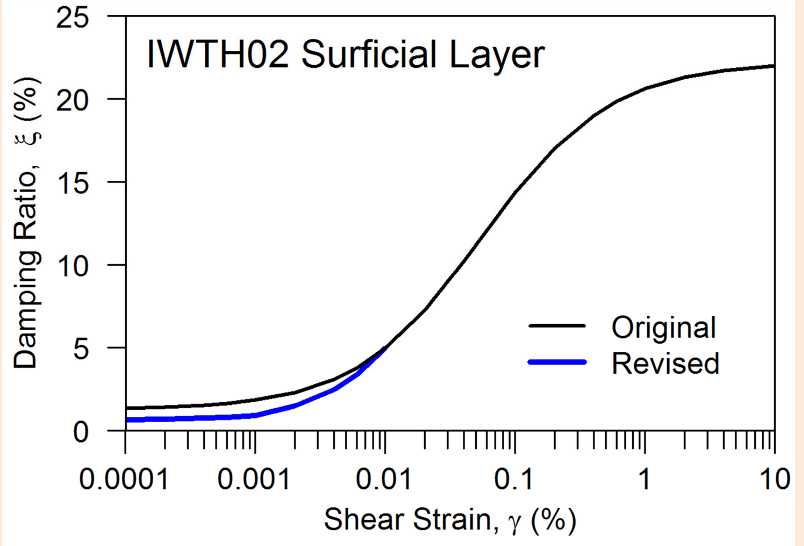
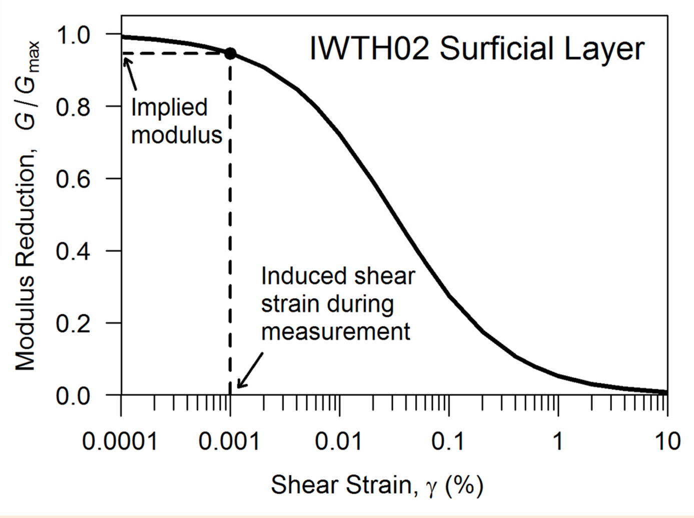


Figure 8: Illustration of the potential measurement bias in G_{max}, using the assumed modulus reduction curve of the surficial layer at IWTH02. If the surface-downhole test induces 0.001% strain in the soil, then the associated shear modulus is actually less than the true G_{max}.



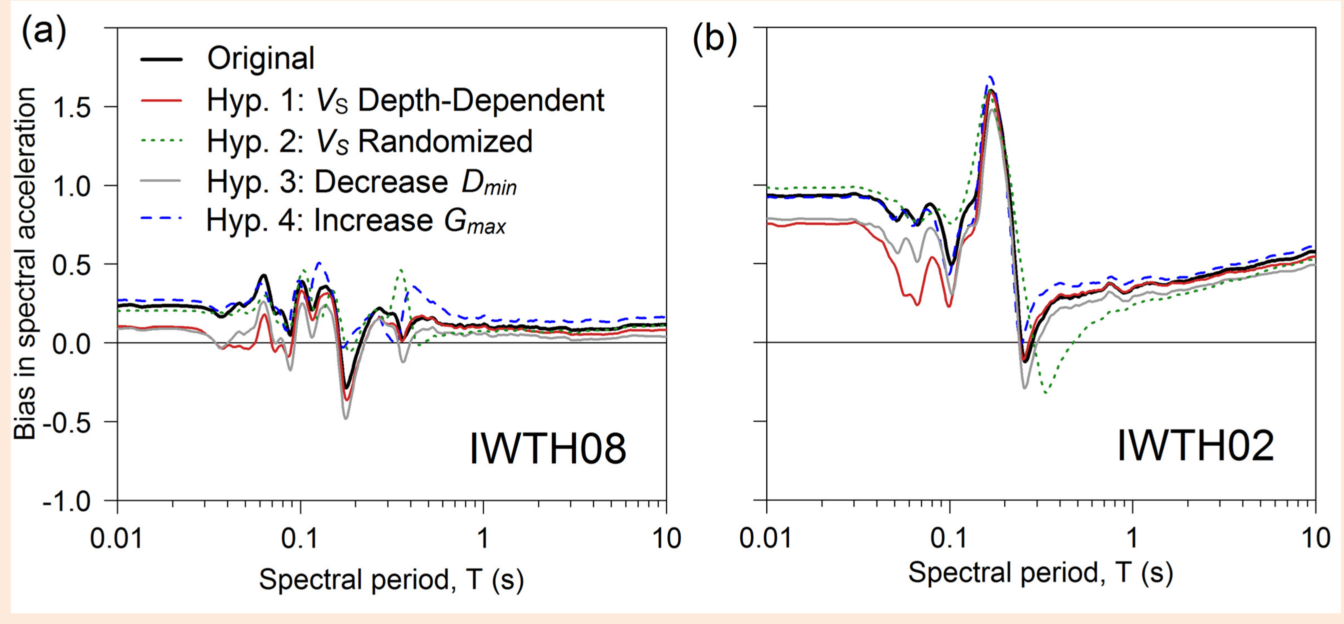


Figure 4. NL model bias versus spectral period for the original soil profiles and those from alternative physical hypotheses, using all the ground motions at each site: (a) IWTH08 (45 records), and (b) IWTH02 (59 records); similar patterns are observed for the L and EQL model biases.

4. Conclusions

- All models are shown to exhibit consistent positive bias (underprediction) at short periods, particularly for small-strain motions.
- Persistent site response model biases at high frequencies suggest that: (1) assumptions regarding the soil profiles and material parameters may need to be readdressed; and/or (2) many of these sites may experience a breakdown in the 1D site-response assumptions.
- Physical adjustments to the assumed shear-wave velocity profile and small-strain damping ratio and have a significant impact on model predictions, more so than changing the constitutive model.
- The most promising physical adjustments for reducing site response bias are the usage of a depth-dependent gradient for the V_S profile, and reducing the small-strain damping ratio. At short periods, these adjustments reduce the model bias anywhere from 20 to 60% at each site. Future work will extend these physical hypothesis tests to more sites in the master database.

5. References

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6. Acknowledgments

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